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The Effect of Perfusate Temperature in a Liquid Cooling System on Heat Strain and Heat Transfer

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Summary

Problem

Military personnel are sometimes required to perform work in hot environments and occasionally in conditions that necessitate use of chemical protective (CP) clothing. Physical activity in these environments can pose a serious health hazard and result in illness or injury, ranging from muscle cramps and nausea to collapse and even death. Microclimate cooling devices have been used to reduce the effects of hot, noxious environments. However, most devices have insufficient cooling capacities to reduce thermal strain significantly when physical work is performed in hot environments.

Objective

The objective of this project was to determine the effectiveness of a liquid cooling system (LCS), operated at three different perfusate temperatures (T_p), to reduce heat strain in personnel required to perform moderate work in a hot environment while encapsulated in CP clothing.

Approach

In this study, 12 subjects walked on a treadmill (3 mph and 2% grade) for 60 min in a hot environment (35°C and 65% relative humidity) while encapsulated in CP clothing. Indices of heat strain (e.g., heart rate, core body temperature, and sweat rate) and heat transfer ($\dot{Q}$) were compared across one control condition (no cooling [NC]) and three experimental conditions with T_p in an LCS of either 10°C (10C), 20°C (20C), or 30°C (30C). Tests were conducted in a counterbalance fashion with each subject exposed to all four conditions.

Results

Indices of heat strain were significantly different among the conditions, except between 20C and 10C. The heat strain data showed the following trend: NC > 30C > 20C ≈ 10C. Final core body temperature was significantly different among NC (38.9°C), 30C, (38.3°C), 20C (37.7°C), and 10C (37.7°C); however, the difference between 20C and 10C was not significant. Final heart rates were different among NC (159 bpm), 30C (141 bpm), 20C (111 bpm), and 10C (106 bpm); however, the difference between 20C and 10C was not significant. Mean skin temperature decreased with lower T_p and was different among all of the conditions with NC

(38.2°C) > 30C (36.3°C) > 20C (33.3°C) > 10C (30.1°C). $\dot{Q}$ increased progressively with decreases in T_p, and it was significantly different among conditions: 30C (267 W), 20C (500 W), and 10C (622 W). However, the relationship between T_p and final $\dot{Q}$ was not linear.

Conclusion

In this study, T_p at 20°C and 10°C significantly reduced heat strain when compared with T_p at 30°C and NC. However, T_p at 10°C did not significantly reduce heat strain further when compared with T_p at 20°C. Although $\dot{Q}$ was significantly different among the cooling conditions, the difference between 30C and 20C was greater (i.e., 500 - 267 = 233 W) than the difference between 20C and 10C (i.e., 622 - 500 = 122 W). The smaller than expected $\dot{Q}$ for 10C may be attributed to cutaneous vasoconstriction potentiated by overcooling.

Introduction

Humans, as homeotherms, regulate body temperature such that core temperature is maintained around 37°C. Thermoregulation involves balancing heat input and output so that homeostasis is achieved and consists of both behavioral and physiological responses. Behavioral responses include changes in posture, activity, or clothing. Physiological responses include changes in blood flow distribution, sweat production, and metabolic heat production. When body heat must be conserved, behavioral responses include bringing the extremities nearer to the trunk, increasing physical activity, or donning additional clothing. Physiological responses include a decrease in peripheral blood flow and an increase in metabolism. In combination, these actions reduce heat loss and enhance metabolic heat retention. Alternatively, when body heat must be dissipated, behavioral responses include a reduction in physical activity and removal of clothing. Physiological responses include an increase in blood flow to the skin and initiation of sweating.

Sometimes desired behavioral changes cannot be accommodated and physiological adjustments are negated (e.g., when work must be done in noxious environments and chemical protective [CP] clothing must be worn). CP clothing is worn to prevent noxious agents from reaching the skin; however, due to its low moisture permeability and high insulating properties, normal avenues for heat loss are compromised. Heat generated metabolically and gained from a hot environment cannot readily be dissipated due to the encapsulating nature of the CP clothing. Impaired heat dissipation can result in heat strain ranging in severity from physical discomfort to illness (e.g., cramps, exhaustion, stroke) and death. Thus, an external source of cooling becomes essential for prevention of heat injury in individuals required to work in hot, noxious environments.

Liquid cooling systems (LCSs) have been explored as a means of militating against hot environments. These types of systems consist of a tight-fitting garment in which a network of plastic tubing is sewn. A chiller is used to cool and pump fluid (e.g., water, ethylene glycol) through the tubing. To be effective, an LCS must have sufficient cooling capacity to extract both metabolic and environmental heat gained.

The cooling capacities of several portable commercial LCSs have been measured in the 108 to 244 W range (Cadarette et al., 1990). Metabolic heat production during rest, light, moderate, and heavy exercise has been measured at 120, 185, 300, and 425 W, respectively (Parsons, 1993). Therefore, it is not surprising that thermal balance cannot be maintained by using these systems when moderate or heavy physical activity is required (Pimental & Avelleni,

1989; Pimental et al., 1987; Speckman et al., 1988). Portable LCSs reduce heat strain, but without maintaining thermal balance when light to moderate exercise is performed in a hot environment (Pimental & Avelleni, 1989; Pimental et al., 1987; Speckman et al., 1988; Vallerand et al., 1991). However, the cooling capacities of portable LCSs are insufficient to reduce heat strain substantially when heavy work is performed in a hot environment (Cosimini et al., 1985; Terrian & Nunneley, 1983). Thus, attempts have been made to construct an LCS capable of extracting sufficient metabolic and environmental heat to maintain thermal balance when high work loads or high-heat exposures are required.

The basis for these efforts lies in the principles of heat transfer. Experiments show that the rate of heat transfer is:

$$\dot{Q} = A \cdot (T_H - T_C) \cdot R^{-1}$$

Where $\dot{Q}$ = heat transfer rate; A = area across which heat is being transferred; T_H = hotter temperature; and T_C = cooler temperature; R = thermal resistance (i.e., R = thickness of the material ÷ thermal conductivity of the material across which heat is being transferred).

In an LCS, heat flow into the system is derived from distinct sources - the body and the environment. Thus, the equation becomes:

$$\dot{Q} = A_{skin} \cdot (\bar{T}_{sk} - T_p) \cdot R^{-1} + A_{env} \cdot (T_{env} - T_p) \cdot R^{-1}$$

A_{skin} = surface area of the skin in contact with the tube; $\bar{T}_{sk}$ = mean skin temperature; T_p = perfusate temperature; R = thermal resistance of the tubing sewn into the suit; A_{env} = surface area of the tube exposed to the environment; and T_{env} = environmental temperature.

Thus, in a given T_{env}, to enhance heat transfer across the tube suit, three dependent variables could be altered, A, R, or T_p. The first variable, A, has received considerable scientific exploration. Increasing the body surface area in contact with cooling tubes has been shown to reduce body heat gain. In a thermal mannikin study, whole-body cooling reduced heat storage by 70% (Fonseca, 1976). In that same study, torso-arm-leg cooling reduced heat storage by 34%, and torso-only cooling reduced heat storage by 7% when compared with no cooling. Shvartz et al. (1974) studied the effects of cooling 10 different body regions in men performing exercise in a hot environment. They found that cooling larger body regions (e.g., back, chest, or thighs) resulted in a greater reduction of thermal strain than when cooling smaller body regions (e.g.,

upper arms, lower arms, or hands). Kaufman and Pittman (1966) reported that thermal strain was reduced further during torso-arm cooling when compared with torso-only cooling. In contrast, Young et al. (1987) found that a combination of torso-arm cooling did not reduce thermal strain further than seen with torso-only cooling. However, they did find that a combination of torso-arm-thigh cooling reduced thermal strain compared with torso-only cooling.

To date, experimentation with the second variable, R, has not taken place. Historically, the same type of tubing has been used in all tube suits and is composed of polyvinyl chloride. The tubing has the distinct advantage of being both rigid enough to prevent pinching, thus avoiding inadvertent restriction of coolant flow, yet flexible enough to be sewn into a tight, circuitous route on the suit.

The aim of this study was to examine the effects of manipulating the third variable, T_p. In previous experiments, T_p in an LCS was set to accommodate the subjects' sense of thermal comfort (Shvartz & Benor, 1971; Webb et al., 1991), to remove a specified percentage of metabolic heat produced (Webb et al., 1970), or to lower the dew point within the protective overgarment (Webb & Annis, 1968). Usually, a T_p of 20°C to 22°C was selected.

Heat transfer, measured on a mannikin, increased directly in proportion to the difference in T_p and the mannikin surface (Fonseca, 1976). However, it is uncertain if this linear relationship holds when cooling is applied to humans. It is a concern that at low T_p, thermoregulatory consequences favoring body heat conservation would be activated and reduce heat transfer from the body. LCSs have been shown to lower $\bar{T}_{sk}$ (Webb & Annis, 1968). $\bar{T}_{sk}$ affects skin blood flow (SkBF) during rest (Brengelmann et al., 1973; Pergola, 1994) and when core temperature is elevated (Johnson et al., 1976; Johnson & Park, 1979; Pergola, 1994; Wenger et al., 1975; Wyss et al., 1974). Because a fourfold to sixfold increase in tissue thermal conductivity has been associated with changes in SkBF (Burton & Bazett, 1936; Keller & Seiler, 1971), $\dot{Q}$ may be restricted when $\bar{T}_{sk}$ is low. The possibility exists that with very cold perfusate (i.e., 10°C) vasoconstriction would be induced, thereby inhibiting heat transfer from the body to the LCS and would not further facilitate $\dot{Q}$.

In this study, T_p in the water-perfused LCS was varied so that the relationship between water temperature (T_w) and $\dot{Q}$ could be examined. T_w was set at either 10°C, 20°C, or 30°C. $\dot{Q}$ and indices of heat strain were compared across a control condition and three experimental conditions.

Methods

Subjects

After a medical review and written consent were given, 8 male and 3 female military personnel served as subjects for this test. Pregnant women were excluded from this study.

Experimental Design

The volunteers participated in four 60-min experimental trials, in an environmentally controlled chamber at 35°C and 65% relative humidity (RH) in which moderate exercise ($\dot{V}O_2 \approx$ 1.4 L/min) was performed. The participants completed the following four experimental conditions in a counterbalanced fashion:

1. No Cooling (NC) (water removed from the tubes)
2. 10°C Water Cooling (10C)
3. 20°C Water Cooling (20C)
4. 30°C Water Cooling (30C)

To minimize treatment interactions, each of the four experimental trials was separated by at least 1 day.

Experimental Procedures

To ensure adequate hydration, the volunteers were instructed to avoid heat exposure, alcohol consumption, and strenuous exercise 24 hr before each trial, and to drink at least 24 ounces of noncaffeinated fluid 12 hr before each trial.

On each test day, the volunteer reported to the laboratory at the same time of day. Before testing, urine specific gravity was assessed to ensure proper hydration. Euhydration was defined as urine specific gravity of < 1.030. For pregnancy detection, a urine sample was tested for the presence of human chorionic gonadotropin.

Before each trial, the volunteers were instrumented with eight skin temperature thermistors (Yellow Springs Instruments, Inc.; Yellow Springs, OH). The thermistors were placed on the left side of the body on the cheek (ch), scapula (sc), abdomen (ab), forearm (fa),

hand (ha), thigh (th), calf (ca), and foot (fo). Rectal temperature (T_{re}) was measured using a disposable thermistor (Sheridan; Argyle, NY) inserted to a depth of 15 cm beyond the anal sphincter. The rectal and skin thermistors were connected to a digital analog recorder (Science Electronics, Inc.; Miamisburg, OH) for continuous visual monitoring and data recording every minute. Heart rate (HR) was recorded by a monitor consisting of electrodes on a chest strap that continuously transmitted a signal to a wristwatch receiver (Polar Heart Watch; Stamford, CT). HR data were recorded as 1-min averages.

After temperature and HR monitors were in place, the volunteers donned a clothing ensemble that consisted of the following layers: (1) shorts, underwear, and socks; (2) tube suit; (3) coveralls and athletic shoes; and (4) a CP ensemble consisting of bibbed trousers, hooded jacket, rubber boots, and butyl rubber gloves, but no gas mask. The clothing ensemble, tube suit, and bioinstrumentation increased the volunteer's weight by 12.2 kg.

After bioinstrumentation was completed, and before entering the chamber, baseline measurements of HR, T_{re}, and eight skin temperatures for computation of $\bar{T}_{sk}$ were recorded for 15 min. During this period, in the cooling conditions, water was circulated through the LCS at the test temperature. Upon entering the chamber, the volunteer walked on a treadmill set at 3 mph and 2% grade until any criterion for experiment termination was reached. The criteria for termination were:

1. T_{re} of $\geq 39.5°C$
2. HR of 90% of the age-predicted maximum (i.e., 220 - age) for 5 min
3. Sweating cessation, nausea, vomiting, retching, syncope, cramps, dizziness, or disorientation
4. Subject requested to stop
5. Subject completed 60 min of exercise

Every 15 min during the test, the volunteer's expired air was collected in a Douglas bag for 2 min. The volume was measured in a 120-L wet spirometer (Collins, Inc; Braintree, MA), and the gas was analyzed with Ametek S 3A/I and Beckman LB2 analyzers (Ametek, Inc.; Pittsburgh, PA) for percent oxygen and percent carbon dioxide, respectively. The volunteer's thermal sensation (TS) was recorded at 15-min intervals throughout the trial using a scale (see Figure 1) that was modified from one presented by Gagge et al. in 1967.

+4 Very Hot
+3 Hot
+2 Warm
+1 Slightly Warm
0 Neutral
−1 Slight Cool
−2 Cool
−3 Cold
−4 Very Cold

Figure 1 – Thermal Sensation Scale.

Ratings of perceived exertion (RPE) were recorded at 15-min intervals throughout the trial using the Borg 15-Point Scale (Borg, 1982).

<u>Liquid Cooling System</u>

An LCS was used to remove heat (i.e., environmental and metabolic heat) from the volunteers. The system consisted of a tight-fitting garment in which a network of plastic tubing was sewn (tube suit) and a chiller that pumped cooled water through the tubing. The tube suit was an elastic garment embedded with a network of Tygon tubing (Norton Performance Plastics; Akron, OH) (inner diameter = 1.66 mm; outer diameter = 3.22 mm). A total of 15.7 m of tubing was distributed over six separate body regions: head/neck (1.6 m), arms (2.9 m), upper torso (2.4 m), lower torso (2.2 m), thighs (2.9 m), and lower legs (3.7 m). Water circulated through the tube suit from a temperature-controlled 30-L reservoir (Model No. HX-150; Neslab; Portsmouth, NH). Both the inlet water temperature (T_{wi}) and the water velocities were kept constant: water velocity was set at 0.6 L/min and T_{wi} was set at either 10°C, 20°C, or 30°C. T_{wi} and outlet water temperatures (T_{wo}) were measured with precision thermistors accurate to ± 0.002°C (Model No. SP034-47; Yellow Springs Instruments, Inc.; Yellow Springs, OH). The thermistors' responses were characterized by the manufacturer: for each thermistor, resistance at three temperatures (i.e., 0°C, 25°C, and 40°C) was measured, and then a resistance-temperature curve was derived using an equation for nonideal semiconductors (Steinhardt & Hart, 1968). The mass water flow ($\dot{m}_w$) was measured with a turbine flowmeter calibrated by the manufacturer (3 points) (EG&G Technology; Phoenix, AZ). The accuracy of the flowmeter was assessed in our laboratory by weighing the water collected from the water loop during a 10-min period. The flowmeter was determined to be accurate within ± 0.01%. Both water flow and temperature measurements were

averaged and recorded over 2-min intervals.

Calculations

$\dot{Q}$ to the LCS was calculated as follows: $\dot{Q} = \dot{m}_w \cdot c_w \cdot (T_{wo} - T_{wi})$. Where $\dot{Q}$ = heat transfer to the LCS; $\dot{m}_w$ = mass of water; c_w = specific heat of water; T_{wo} = water temperature on the outlet side; T_{wi} = water temperature on the inlet side (Halliday et al., 1988). $\dot{Q}$ is the sum of heat transferred from the body ($\dot{Q}_{body}$) and the environment ($\dot{Q}_{env}$). $\dot{Q}_{env}$ was estimated using a regression equation previously derived: $\dot{Q}_{env}$ (W) = 7.0 (Watts/°C) * (T_{lyr1} - T_w [°C]) + 5.9 (Canine & Bothorel, 1997).

Total body sweat rate (SR) was calculated from nude body weight loss during heat exposure corrected for urine output and fluids consumed. Evaporative sweat rate (ESR) was estimated from clothed body weight loss (i.e., recorded while the subjects were fully instrumented and clothed in the CP ensemble), accounting for urine output and fluid consumption. Evaporative heat loss (E_{sk}) was calculated as: E_{sk} = ESR · Latent Heat of Vaporization of Water.

$\bar{T}_{sk}$ was calculated as: $\bar{T}_{sk} = (0.07T_{ch}) + (0.175T_{sc}) + (0.175T_{ab}) + (0.14T_{fa}) + (0.05T_{ha}) + (0.19T_{th}) + (0.13T_{ca}) + (0.07T_{fo})$ (Hardy & DuBois, 1938). Rate of heat storage (S) was calculated using the change in $\bar{T}_{sk}$ and T_{re}, body weight, and the specific heat of the body (0.965 cal·kg^{-1}·°C^{-1}).

Body composition was assessed using four skinfold measurements. Body density was calculated using the Durnin and Womersley (1974) equations. Percent body fat was calculated using the equation derived by Siri (1956).

Statistical Analysis

Analysis of variance with repeated measures on the independent variables of time and condition was used to analyze the dependent variables of $\bar{T}_{sk}$, T_{re}, HR, S, TS, RPE, oxygen consumption ($\dot{V}O_2$) and $\dot{Q}$. These data were analyzed across time at intervals 15, 30, 45, and 60 min; and across conditions NC, 10C, 20C, and 30C. $\bar{T}_{sk}$, T_{re}, HR, and S were recorded as averages over 3 min. In the cases of early termination, an average over the final 3 min of the test were used as final values. Tolerance time, SR, and S were analyzed between cooling temperatures using analysis of variance with repeated measures. When significant differences were found, Tukey's test of critical difference was conducted for post hoc analysis. In all

statistical tests, a value of $p < 0.05$ was accepted as significant. All values are expressed as mean ± standard deviation (*SD*).

Results

Subjects

The physical characteristics of the subjects are shown in Table 1.

Table 1 – Physical Characteristics (mean ± *SD*)

Variable	**Total** $N = 11$	**Males** $N = 8$	**Females** $N = 3$
Age (y)	34 ± 7	34 ± 7	33 ± 9
Height (cm)	173.3 ± 5.7	175.6 ± 4.1	167.2 ± 5.3
Weight (kg)	72.9 ± 8.6	74.4 ± 8.5	68.7 ± 9.1
Body Fat (%)	20.4 ± 8.8	16.4 ± 5.4	27.2 ± 6.2

Tolerance Time

In 10C and 20C, all of the volunteers completed the 60-min test. In 30C and NC, tolerance time was less, but not significantly different from 10C and 20C (58 ± 5 min, 56 ± 6 min, 60 ± 0 min, and 60 ± 0 min, respectively). The termination criteria based on HR accounted for both early terminations in 30C. For the six early terminations in NC, 2 volunteers were withdrawn based on high T_{re}, and 4 were withdrawn based on high HR.

Body Temperatures:

T_{re} recorded in the final minutes of the heat exposure (final T_{re}) was significantly different among NC (39.0 ± 0.5°C), 30C (38.3 ± 0.4°C), and 20C (37.7 ± 0.3°C). However, there was no difference between final T_{re} for 20C and 10C (37.7 ± 0.4°C). The increase in T_{re} over time, from min 15 to min 60, was significant for all conditions (see Figure 2).

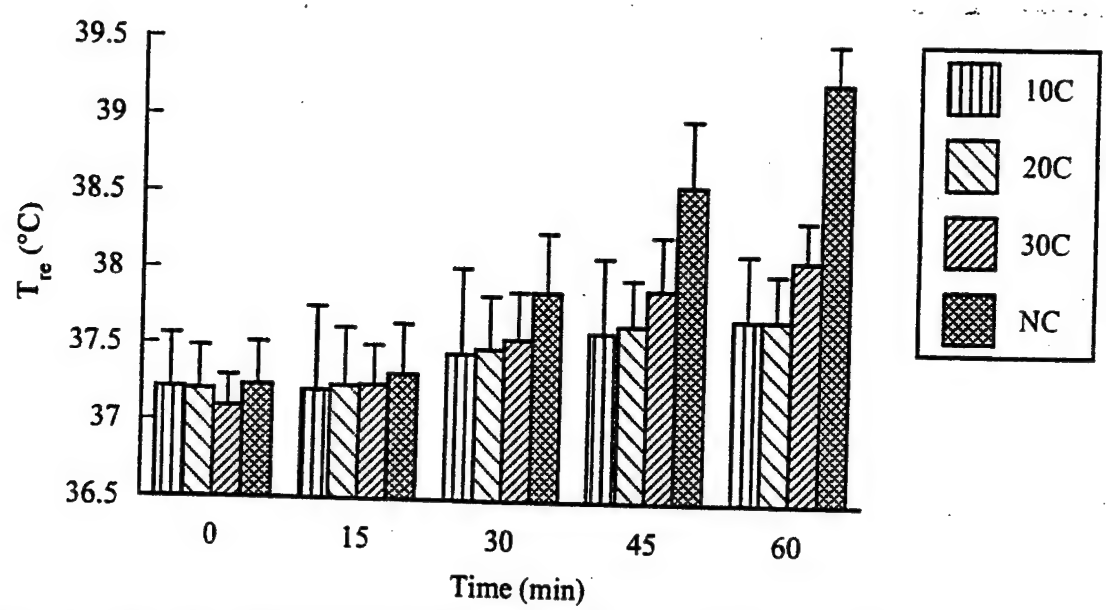

Figure 2 – Core body temperature with time. There was a significant difference among conditions, except between 10C and 20C.

Final $\bar{T}_{sk}$ was significantly different among NC (38.2 ± 0.8°C), 30C (36.3 ± 0.4°C), 20C (33.3 ± 1.0°C), and 10C (30.1 ± 0.9°C). The increase in $\bar{T}_{sk}$ over time, from min 15 to min 60, was significant for NC, 30C, and 20C, but not for 10C (see Figure 3).

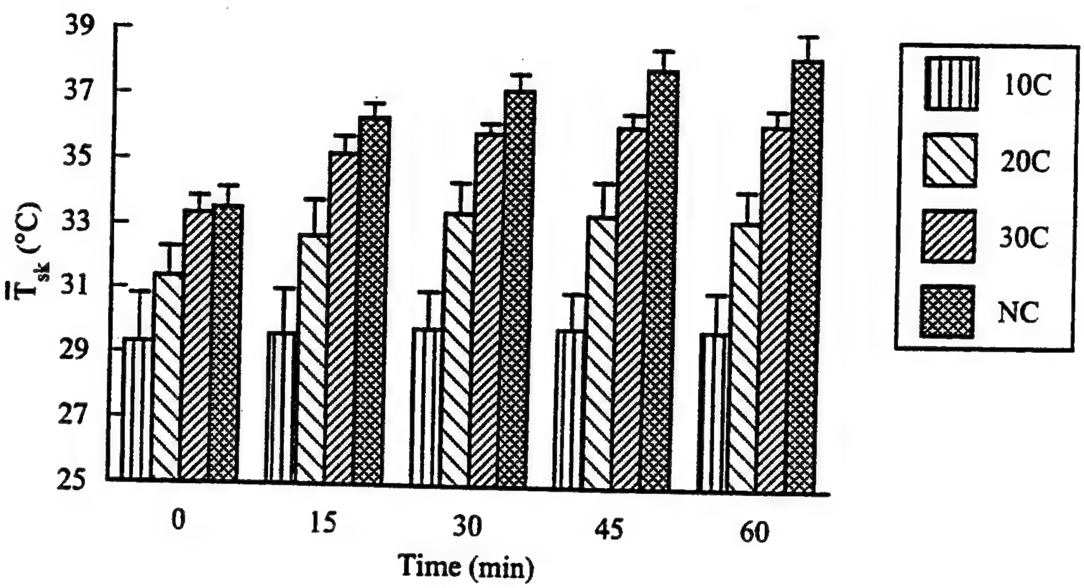

Figure 3 – Mean skin temperature with time. There was a significant difference among conditions.

Cardiopulmonary

HR during the final minutes of the test (final HR) was significantly different among NC (159 ± 16 bpm), 30C (141 ± 20 bpm), and 20C (111 ± 18 bpm). The difference in final HR between 20C and 10C (106 ± 15 bpm) was not significant. The increase in HR, from min 15 to min 60, was significant for NC, 30C, and 20C, but not for 10C (see Figure 4).

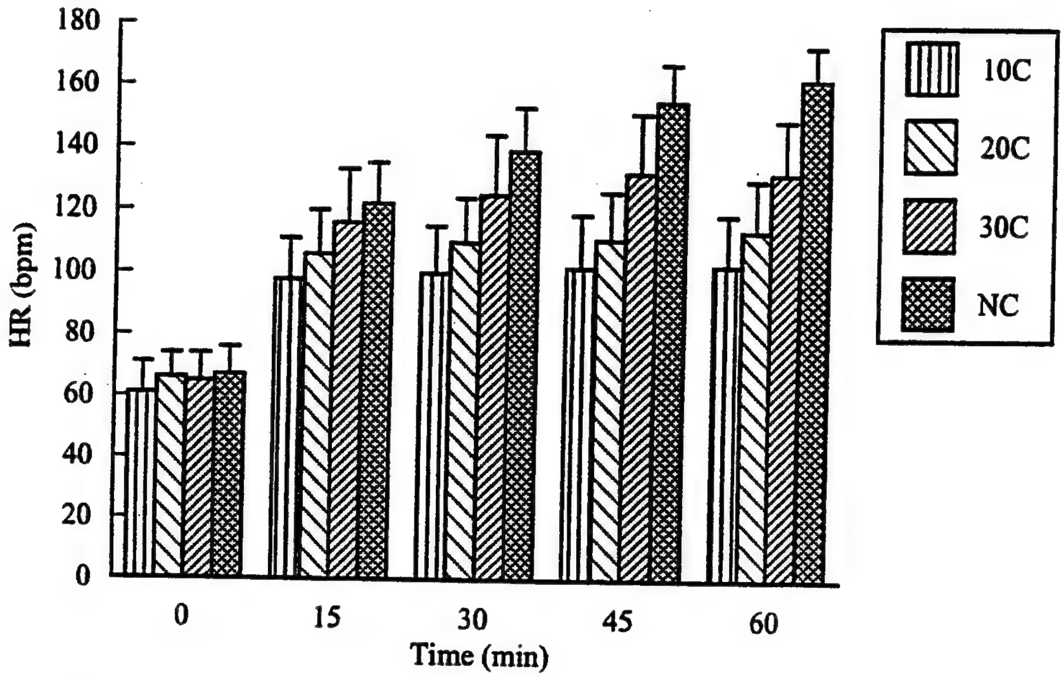

Figure 4 – Heart rate with time. There was a significant difference among conditions, except between 10C and 20C.

$\dot{V}O_2$ taken in the last 2 min of exercise did not differ between 10C (1.3 ± 0.3 L·min^{-1}) and 20C (1.4 ± 0.2 L·min^{-1}); 20C and 30C (1.5 ± 0.1 L·min^{-1}); nor 30C and NC (1.6 ± 0.2 L·min^{-1}). The values for $\dot{V}O_2$ showed the general trend NC > 30C > 20C > 10C; however, $\dot{V}O_2$ was not significantly different between 10C and 20C, nor between 20C and 30C.

Ratings of Perceived Exertion and Thermal Sensation

Final RPE was significantly different between NC and all other conditions (16 ± 3). Final RPE was significantly higher in 30C (13 ± 3) than in 10C (11 ± 3). Final RPE reported during 20C (11 ± 2) was not significantly different from those reported in 10C or 30C. The increase in RPE over time, from min 15 to min 60, was significant in all conditions.

Final TS was not different between 10C (-1 ± 1) and 20C (+1 ± 1), but final TS was significantly higher in 30C (+3 ± 1) and NC (+4 ± 1) than in 10C and 20C. TS increased over time, from min 15 to min 60 during NC.

Sweat Rate

Whole-body SR was significantly different among NC (25 ± 11 mL · min^{-1}), 30C (18 ± 7 mL · min^{-1}), 20C (8 ± 4 mL · min^{-1}), and 10C (5 ± 3 mL · min^{-1}).

Evaporative Sweat Rate

In the cooling conditions, ESR measurement frequently resulted in a negative rate. Therefore, in the cooling conditions neither ESR nor E_{sk} could be assessed statistically.

Heat Transfer

Final $\dot{Q}$, computed as an average over the final 4 min of the test, was significantly different among 30C (267 ± 24 W), 20C (500 ± 48 W), and 10C (622 ± 53 W). The increase in $\dot{Q}$, from min 15 to min 60, was significant for all conditions (see Figure 5).

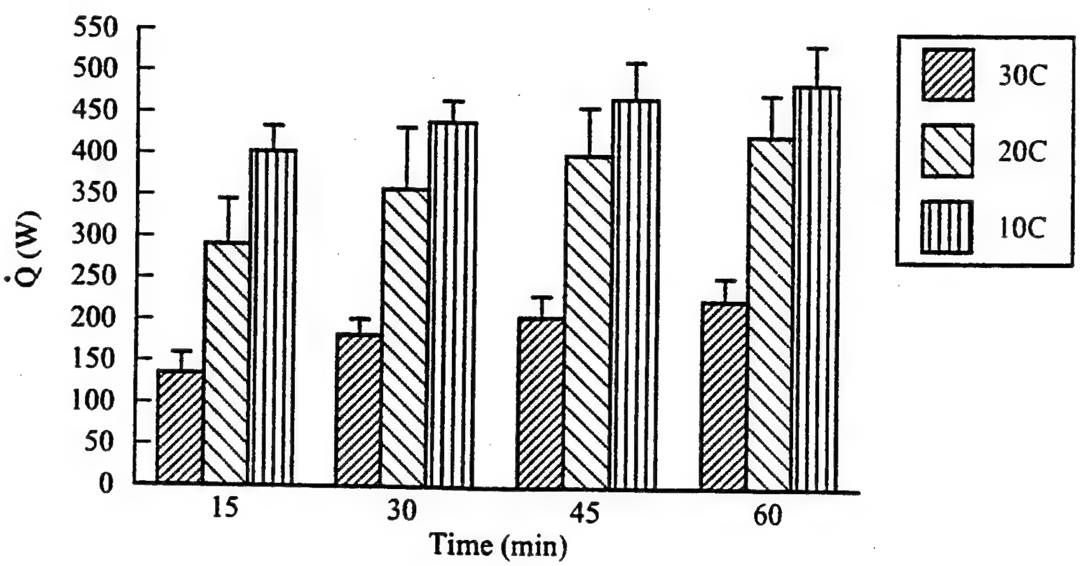

Figure 5 – Heat transfer with time. There was a significant difference among conditions.

$\dot{Q}_{env}$, estimated from a regression equation, was significantly different between the conditions (see Figure 6).

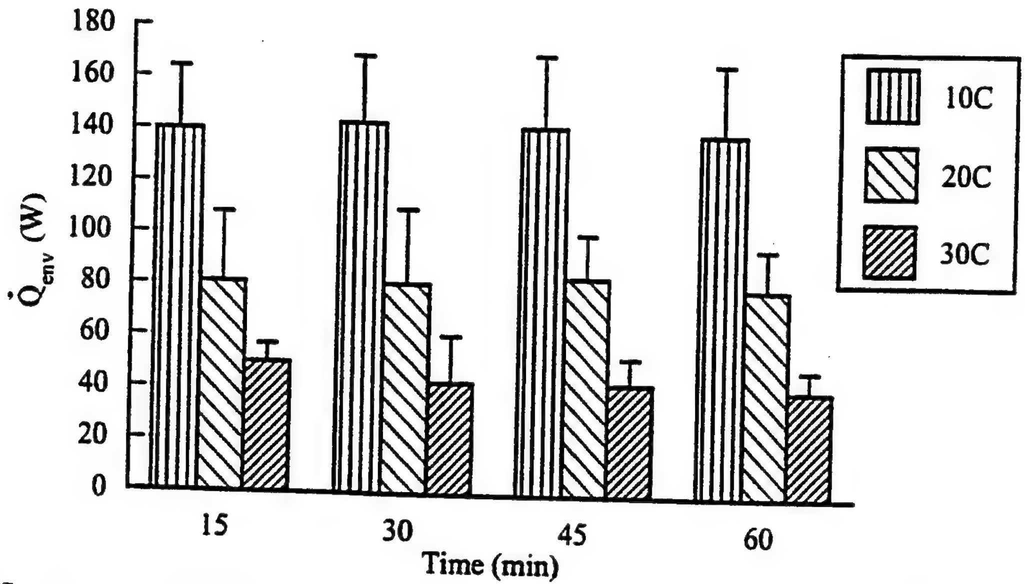

Figure 6 - Heat transfer from the environment with time. There was a significant difference among conditions.

Once $\dot{Q}_{env}$ was estimated from the regression equation, an estimate of $\dot{Q}_{body}$ was obtained (see Figure 7).

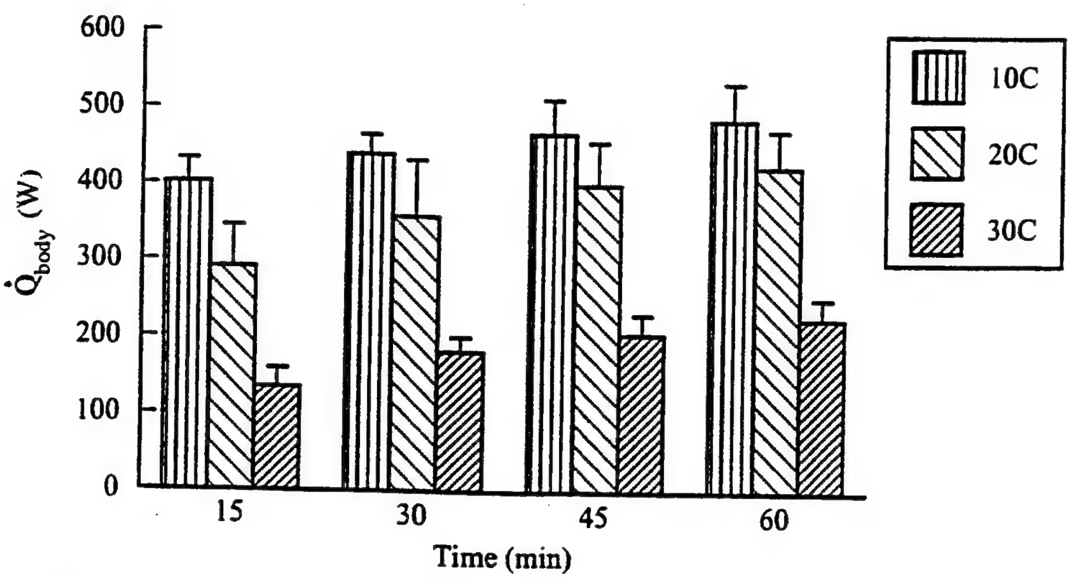

Figure 7 - Heat transfer from the body with time. There was a significant difference among conditions.

Discussion

LCS research has been largely descriptive, because, in most cases, $\dot{Q}$ could not be quantified due to the lack of appropriate instrumentation. In the past, system effectiveness was compared across experimental and control trials using indices of heat strain. If there were significant reductions in these indices then a system was said to be effective. We hypothesized that the LCS utilized in this study would provide sufficient cooling to reduce heat stress, that physiological variables used as indices of heat strain would be lower when cooling was provided, and that less heat strain would be evident with lower T_w.

Control Condition

During NC, a progressive increase in HR from min 15 to min 60 was seen (see Figure 4). Cardiac upward drift, an increase in HR during steady state exercise, has been found when work is performed in CP clothing while in a hot environment (Avellini, 1984; Pimental et al., 1986). The literature shows that cardiac drift has been associated with reductions in central blood volume (CBV) (Rowell et al., 1966) presumably due to increases in SkBF and progressive loss of body fluids due to sweating. Although neither blood volume nor SkBF were measured in this study, we believe the cardiac drift seen was attributable to a decrease in CBV potentiated by body fluid loss and increased SkBF. Body fluid loss was approximated by comparing rate of fluid consumption, estimated fluid absorption rate, and SR. In this study, the subjects were allowed to drink water ad libitum. However, fluid replacement was encouraged since individuals voluntarily dehydrate during exercise in the heat (Greenleaf et al., 1983). In general, fluid consumption (24 ± 11 mL $\cdot$ min^{-1}) matched with fluid lost due to sweating (25 ± 11 mL $\cdot$ min^{-1}). It is unlikely that body fluid replacement matched body fluid loss because gastric emptying of water is relatively slow (15 mL $\cdot$ min^{-1}) (Foster, 1993) when compared with the sweat rate. It has been shown previously that SkBF can be estimated roughly by calculating body conductance (body conductance = $\dot{V}O_2 \cdot [T_{re} - \bar{T}_{sk}]^{-1}$); further, that SkBF is inversely proportional to the temperature difference between the core and skin ($SkBF \propto 1 \cdot [T_{re} - \bar{T}_{sk}]^{-1}$) (Kerslake, 1972). In this study, body conductance increased, and the temperature difference between T_{re} and $\bar{T}_{sk}$ decreased over time, suggesting that SkBF was increasing. Thus, an increase in SkBF, along with plasma fluid loss, likely potentiated the increase in HR over time in the NC condition. This is supported by the cardiac responses of 4 individuals whose HR exceeded 90% of age-predicted maximum resulting in early test termination.

In NC, RPE increased over time. The RPE scale was devised to identify perceived differences in exercise intensity (Borg, 1970), and RPE was scaled so that linearity between HR and RPE was maximized (i.e., RPE = HR $\cdot$ 10^{-1}) (Borg, 1982). Borg's subsequent research (as cited in Mihevic, 1981) has shown that RPE is highly correlated with HR ($r = 0.8$ to 0.9). In this study, RPE in the NC condition was only moderately correlated with HR ($r = 0.5$). RPE increased over time in this study, although there was no increase in work load. These findings are supported by others who reported RPE to be independent of HR when heat stress is imposed (Kamon et al., 1974; Nobel et al., 1973).

In NC, sweat evaporated at a rate of 20 ± 10 mL $\cdot$ min^{-1} $\cdot$ m^{-2}. Thus, evaporatory heat loss (80 ± 40 W $\cdot$ m^{-2}) was substantially less than metabolic heat production (295 ± 28 W $\cdot$ m^{-2}). When an individual is encapsulated in CP garments, sweating is not a particularly effective thermoregulatory response and can lead to cardiovascular compromise. The CP ensemble has low vapor permeability (Goldman, 1988); thus, sweat cannot readily evaporate. When wearing CP clothing, body fluid is lost with no commensurate cooling. However, the body also dissipates heat produced by muscular activity via conduction, convection, and radiation.

In NC, $\bar{T}_{sk}$ (38.3°C) was higher than ambient temperature (36°C). While this implies the possibility of heat transfer to the environment, the rate of heat transfer between the body and the environment is affected by clothing. In this study, the subjects wore multiple layers of clothing. The insulation of any clothing ensemble is determined by the characteristics of its components. Although the thermal resistance of the clothing ensemble was not measured, thermal resistance of its layers have been reported previously (Goldman, 1988). Thermal insulation of various tube suits, drained of perfusate, were measured when worn under an air crew helmet, socks, boots, and coveralls and determined to be between 1.8 and 2.0 Clo (Fonseca, 1976). The CP garment is also highly insulative with a Clo value of 1.97 without mask, hood, and gloves and a Clo value of 2.44 when mask, hood, and gloves are worn (Goldman, 1988). Due to the high thermal resistance of components of the clothing ensemble used in this study, heat transfer from inside the ensemble to the environment was restricted. Therefore, if heat transfer from the body to the microenvironment under the CP clothing ensemble exceeded heat transfer through the garment to the environment, air temperature within the microenvironment would increase until the air temperature in the microenvironment under the CP ensemble could be greater than ambient temperature (T_a). Temperatures between clothing layers were not measured in the NC condition, but since the rate of metabolic heat production and the rate of heat transfer through the body exceed the heat transfer capabilities of the clothing ensemble, it is likely that the temperature within the microenvironment was somewhat higher than the T_a. Both the low moisture

permeability and the high insulating properties of CP clothing prevent heat loss through normal avenues, and heat generated metabolically cannot be readily dissipated. As seen in Figure 8, a substantial quantity of body heat accumulated in a very short period of time. For two of the subjects, tests were terminated early because T_{re} reached 39.5°C.

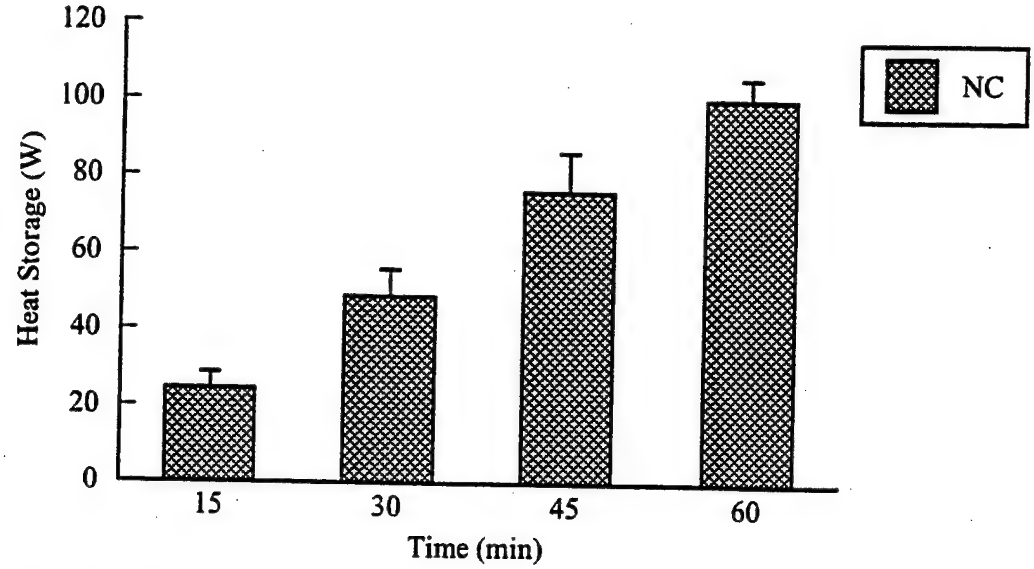

Figure 8 – Body heat storage with time in NC condition. There was a significant increase over time.

Cooling Conditions

LCSs have been explored as a means of reducing the effects of high-heat environments. Efforts to increase the effectiveness of LCSs lie in application of the principals of thermodynamics. In this study, $\dot{Q}$ and standard indices of heat strain were compared across T_w (i.e., 10°C, 20°C, and 30°C) to determine the optimal T_w.

Heat Transfer

This study provided an opportunity to quantify $\dot{Q}$. Because the cooling system was instrumented with highly accurate thermistors and flowmeters, heat transferred to the LCS could be calculated. Given that $\dot{Q}$ is proportional to the difference in temperature between an object and its environment, we hypothesized that as the T_w decreased, the rate of heat transfer to the LCS would increase. Although this trend was seen, the relationship between T_w and $\dot{Q}$ displayed a trend toward nonlinearity (see Figure 9). The difference between 30C and 20C was greater (i.e., 500 - 267 = 233 W) than the difference between 20C and 10C (i.e., 622 - 500 = 122 W).

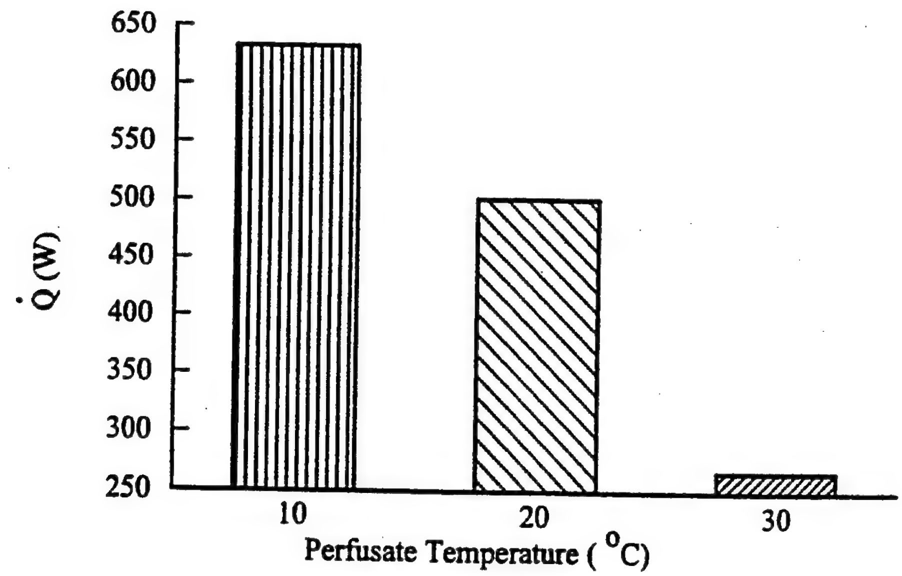

Figure 9 – Relationship between heat transfer and water temperature.

$\dot{Q}$ represents the sum of heat gained on two sides of the tube suit; the body side ($\dot{Q}_{body}$) and the environment side ($\dot{Q}_{env}$). As reported by others (Fonesca, 1976), in this study $\dot{Q}_{env}$ increased linearly with the difference between T_a and T_w. Since $\dot{Q}$ data revealed a nonlinear trend with T_w, and $\dot{Q}_{env}$ was related to T_w in a linear relationship, then $\dot{Q}_{body}$ was apparently related to T_w in a nonlinear fashion. If differences in $\dot{Q}_{body}$ exist among the conditions, then differences in heat strain indices would be expected. In fact, we found that, in general, heat strain indices were greatest for the 30C condition but not different between the 10C and 20C conditions.

Heat Strain Indices

When heat strain indices were compared across the NC and cooling conditions, it was evident that heat stress was less when cooling was provided. In 30C, SR, T_{re}, $\bar{T}_{sk}$, and HR were lower than in NC. Although the physiological variables examined indicate that heat stress was lower in 30C than in the NC, the 30C failed to prevent substantial body heat storage (57 W · m^{-2}), with metabolic heat production (275 W · m^{-2}) greater than cooling ($\dot{Q}_{body}$ = 187 W · m^{-2}). This imbalance between heat generation and heat dissipation was reflected in the elevated heat strain indices. In 30C, a significant increase occurred in both T_{re} and $\bar{T}_{sk}$. In response to this internal thermal stimulus, SR was elevated to 18 ± 7 mL · min^{-1}, well above insensible levels. Once again, presumably due to a loss in CBV, HR increased over time (final HR = 141 ± 20 beats·min^{-1}). HR, meeting the criteria for test termination, accounted for the two early terminations in these trials.

With a T_w of 30°C, tolerance time was extended and heat strain was reduced when compared with the NC condition. The cooling device reduced heat strain by extracting heat from the subject and from the microenvironment under the CP clothing. The temperature within the microenvironment (i.e., T_{lyr1}) rose during the first 15 min of the heat exposure but was maintained near T_a (T_{lyr1} = 35.8 ± 1.7°C). In conclusion, while the LCS reduced thermal stress when compared with the NC conditions, subjects were unable to maintain thermal balance, and heat storage ensued.

Cooling with water at 10°C and 20°C were more effective in reducing heat strain when compared with cooling with water at 30°C. With the lower T_w (i.e., 10C and 20C), significant reductions in HR, T_{re}, SR, and $\bar{T}_{sk}$ were evident when compared with values obtained at the higher T_w (i.e., 30C). However, the additional benefit of cooling at 10C versus 20C was not clearly evident. Although $\bar{T}_{sk}$ was higher during 20C than during 10C, T_{re} was not different. This suggests greater cooling of skin and subcutaneous fat of the superficial shell and no difference in cooling of the body core in 10C or in 20C.

In each of the cooling conditions, water was circulated in the tube suit while the subject rested outside the chamber. This resulted in heat transfer from the body to the cooling system prior to commencement of heat exposure or exercise. At the end of the 10-min rest period, $\dot{Q}_{body}$ was approximately 218 ± 24 W for 10C, 138 ± 28 W for 20C, and 30 ± 12 W for 30C. Since resting energy expenditure is about 100 W at rest, heat loss to the LCS was greater than metabolic heat production in 10C and 20C. When heat loss is greater than heat production, the body initiates mechanisms to protect core temperature.

The superficial shell functions to moderate heat exchange between the body and the environment. This is accomplished by controlling SkBF, thereby altering tissue conductivity and the thermal gradient between the shell and the core and between the shell and the environment. The rate at which heat transfers through body tissue from the core to the periphery is a function of both conduction and convection. Heat transfer by these combined avenues has been termed effective conductivity ($\mathcal{K}_{eff}$) (Burton & Bazett, 1936). It has been shown previously that when SkBF is minimal, $\mathcal{K}_{eff}$ approaches in vitro values for tissue conduction (Cooper & Trezek, 1971; Veicsteinas et al., 1982). Factors influencing $\mathcal{K}_{eff}$ are tissue thickness, tissue type, SkBF, and thermal drive (i.e., $T_{re} - \bar{T}_{sk}$). In this study, the subjects served as their own controls; therefore, between conditions, the rate of heat transfer through the body was affected only by differences in SkBF and/or thermal drive, not tissue type or thickness. At min 60, the difference in thermal drive between 10C and 20C was greater (i.e., 7.9°C - 4.4°C = 3.5°C) than the difference

between 20C and 30C (i.e., 4.4°C - 1.9°C = 2.5°C). Thus, if SkBF were the same among conditions, then the difference in $\mathcal{K}_{eff}$ would be greater between 10C and 20C than between 20C and 30C; further, a greater difference in $\dot{Q}_{body}$ would be expected between 10C and 20C than between 20C and 30C. However, $\dot{Q}_{body}$ for 10C (486 ± 48 W) was only slightly higher than $\dot{Q}_{body}$ for 20C (424 ± 49 W), whereas, $\dot{Q}_{body}$ for 20C was considerably greater than $\dot{Q}_{body}$ for 30C (226 ± 27 W). These findings suggest that in the 10C condition a reduction in SkBF altered $\mathcal{K}_{eff}$ and resulted in a reduction of heat transfer from the body.

Conclusion

Compared with the NC condition, heat strain was reduced in each of the cooling conditions. Significant improvements were found in heat strain indices with the lower cooling temperatures (i.e., 10C and 20C) when compared with the highest cooling temperature (i.e., 30C). No distinct advantage of cooling at 10C was evident when compared with cooling at 20C.

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Decreasing perfusate temperature (T_p) in a liquid cooling system (LCS) leads to a proportional increase in heat transfer ($\dot{Q}$) when measured on a mannikin. However, it is uncertain if the linear relationship between T_p and $\dot{Q}$ holds when cooling is applied to humans. The purpose of this study was to determine the effectiveness of three different T_p to reduce heat strain in personnel required to walk on a treadmill (3 miles·hr^{-1} at 2% grade) for 60 min in a hot-humid environment (35°C and 65% relative humidity). Indices of heat strain and $\dot{Q}$ were measured in 12 subjects during one control condition (no cooling [NC]) and three experimental conditions with T_p of either 10°C (10C), 20°C (20C), or 30°C (30C). In this study, 10C and 20C significantly reduced heat strain when compared with 30C and NC. However, 10C did not significantly reduce heat strain further when compared with 20C. Although $\dot{Q}$ was significantly different among the cooling conditions, the difference between 30C and 20C was greater (i.e., 500 - 267 = 233 W) than the difference between 20C and 10C (i.e., 622 - 500 = 122 W). The smaller than expected $\dot{Q}$ for 10C may be attributed to cutaneous vasoconstriction potentiated by overcooling.

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